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Pentaquark Searches at CDF

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Abstract

Experimental results of a search for the $\Xi_{3/2}(1860)$ cascade pentaquark state in data collected with the CDF 2 Detector in Run II at the Tevatron are presented. No evidence for these states in the neutral $\Xi^-\pi^+$ and doubly charged $\Xi^-\pi^-$ modes has been found. Preliminary upper limits on yields at 1862 MeV/c^2 relative to the well established resonance $\Xi^*(1530)^0$ are presented.

1 Introduction

Evidence for an exotic pentaquark state $\Theta^+(1540)$ with strangeness $S = +1$ has been claimed by a number of experimental groups. Enhancements with a significance of 4.4 to 7.0 standard deviations have been observed in the invariant mass of K^+N in photoproduction [1] and in pK^0_s [2]. The signals seen have been assigned to a $\Theta^+(1540)$ state. These results have inspired a search for other exotic baryon states. The NA49 Collaboration has reported [3] the observation of a strangeness $S = -2$, isospin I =3/2 state $\Xi^{--}_{3/2} \to \Xi^-\pi^-$. An indication of a neutral mode in $M(\Xi^-\pi^+)$ has been demonstrated [3] as well. Recently the H1 Collaboration at HERA has published [4] an observation of a narrow anti-charmed baryon state in the mode $D^{*+}\bar{p}$ at $\sim$3099 MeV/c^2 and interpreted this as a heavy pentaquark Θ^0_c.
The pentaquark state Θ^+, according to the chiral soliton model [5], is considered as a bound state of five quarks. Experimental evidence for pentaquark Θ^+ suggested the existence of other pentaquark partners classified within the antidecuplet $\overline{10}$ representation [5] or the $\overline{10}_f \oplus 8_f$ multiplet as predicted by the constituent quark model approach in [6].
The experimental status of pentaquark baryons includes some controversy. The signal of Θ^+ claimed by [1, 2] is not confirmed by [7]. The cascade pentaquark claimed by [3] has not been seen by [8]. Negative results on both Θ^+ and $\Xi^{--}_{3/2}$ have been reported by large statistics experiments [9]. These experiments exploit their excellent mass resolution and large data samples to calibrate the mass spectra of interest by well established states like $\Lambda(1520) \to pK^-$ and $\Lambda^+_c \to pK^0_s$ (for Θ^+ searches) and $\Xi^*(1530)^0 \to \Xi^-\pi^+$ (for $\Xi_{3/2}$ searches).

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Recently the CDF Collaboration undertook a comprehensive search for several pentaquark states using its Run II 220 pb^{-1} of data taken with the upgraded CDF 2 Detector. We present here the particular search for the cascade pentaquark $\Xi_{3/2}$ through its modes $\Xi^0_{3/2} \to \Xi^-\pi^+$ and $\Xi^{--}_{3/2} \to \Xi^-\pi^-$, both of which involve the doubly strange cascade baryon Ξ^- in the final state. The analysis is based on two data samples. The first one was collected by a trigger selecting events with at least two tracks of opposite charge each, having a momentum above 2.0 GeV/c and an impact parameter measured by the CDF silicon detector to be larger than 100 μm. The total momentum of both tracks was required to be larger than 5.5 GeV/c. This "two displaced track trigger" sample is enriched by events with heavy quarks decaying via hadronic modes. A complementary dataset was taken with a trigger requiring an inclusive jet of transverse energy E_T >20 GeV.

2 Cascades in the CDF 2 Detector

The final state cascade baryon Ξ^- [1] decays almost 100% of time into $\Lambda^0\pi^-$, with a subsequent decay of the Λ^0. Since the days of bubble chamber experiments this spectacular mode has been identified and reconstructed as a single track vertex (we call it here `VERTEX_1`) formed by a kinked track, presumably the π^-, followed in the fiducial volume by another, V^0-vertex (`VERTEX_2`), presumably the Λ^0 decaying to $p\pi^-$, as sketched at Fig.1. In our analysis `VERTEX_2` was subjected to a 3-dimensional fit. Then the three tracks $p\pi^-$ and $\pi^{+,-}$ were fitted to a common 3-dimensional vertex with the constraint that $M(p\pi^-) = M^{\Lambda^0}_{PDG}$ and that `VERTEX_2` points back to `VERTEX_1`, see also Fig.1.

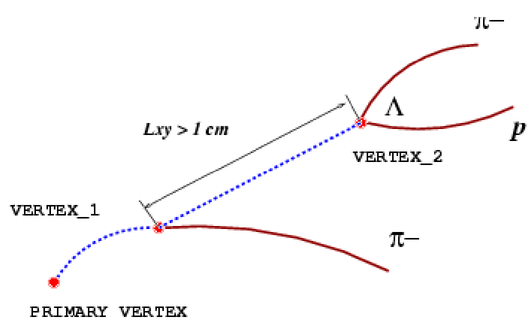

Figure 1: Sketch of the cascade decay topology. The Λ^0 candidates with $M(p\pi^-) \in M^{\Lambda}_{PDG}\pm 5\text{MeV/c}^2$ were fitted to the vertex and the 2-dimensional $\chi^2_{r\phi} < 49.0$ was required. For Ξ candidates $M(p\pi^-\pi_{kink}) \in M^{\Xi}_{PDG}\pm 60\text{MeV/c}^2$ and no $p\pi^-\pi_{kink}$ vertex fit quality χ^2 cut were required. The Ξ and Λ vertices are separated by more than 1 cm in the transverse plane and have an impact parameter $d_0(\Xi)$ <150 μm defined in the transverse plane as well.

The resulting invariant mass spectrum of cascade candidates $M(\Xi^- \to \Lambda^0\pi^-)$ is shown on Fig.2. The clear signal at the Ξ^- mass is seen on top of a large combinatorial background.

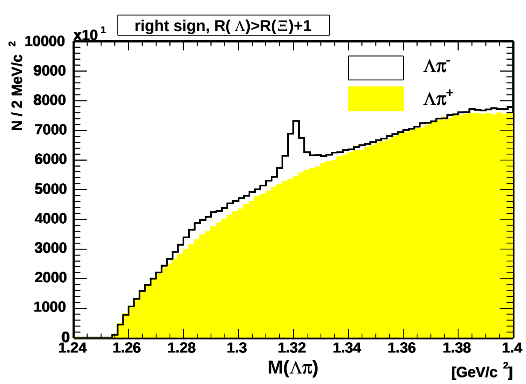

Figure 2: The invariant mass spectrum of $M(\Lambda^0\pi^-)$ after vertex fits described above. The cascade signal is present with a large combinatorial background. The shaded histogram corresponds to the wrong charge combinations $M(\Lambda^0\pi^+)$.

The long lifetime of Ξ^- hyperons ($c\tau$=4.91 cm) permits reconstruction of their tracks from hits in the CDF silicon tracker (SVX II). A novel technique developed by CDF uses the vertex position and momentum of

[1] Unless otherwise stated all references to the specific charge combination imply the charge conjugate combination as well.

a cascade hyperon fitted in the CDF outer tracker to seed the hyperon tracking in SVX II. This procedure results in a substantial background reduction and improved vertex and impact parameter resolution of the Ξ^-, see Fig. 3. The overall relative efficiency of the hyperon reconstruction with SVX II hits is ∼40%. The yields of cascades in the CDF 2 Detector are larger by a factor of ∼20 than the ones found by the NA49 experiment [3].

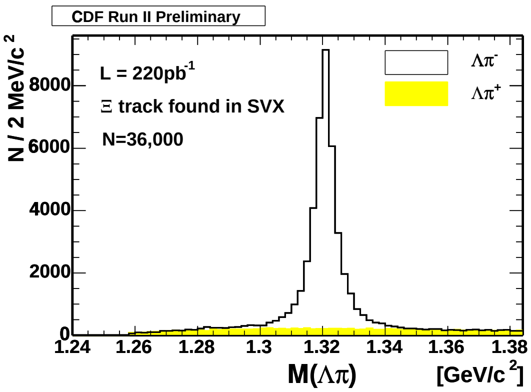

Figure 3: The invariant mass spectrum of Ξ^- hyperons which have tracks successfully reconstructed in the silicon tracker. A cut on impact parameter $d_0(\Xi)$ <150 μm was applied, selecting hyperons produced promptly in the primary vertex region. The very clean signal based on the data sample of integrated $\mathcal{L}$=220 pb^{-1} taken by the two displaced track trigger contains ∼36000 events. The analogous signal (not shown here) for the inclusive jet E_T >20.0 GeV dataset of the same $\mathcal{L}$ contains ∼4870 events.

3 Pentaquarks in the $\Xi^-\pi^+$ and $\Xi^-\pi^-$ Decay Modes

The hyperon tracks reconstructed in SVX II with mass $M(\Xi) \in M^{\Xi}_{PDG} \pm 10$ MeV/c^2 (see Fig. 3) were combined with all remaining tracks with P_T >400 MeV/c and 3 or more hits in the SVX II tracker. Then the track pairs $\Xi^-\pi^{+,-}$ were subjected to a vertex fit constrained by the requirement for the secondary vertex to point to the primary one. The invariant mass spectra $M(\Xi^-\pi^{+,-})$ are shown in Fig. 4 and 5.

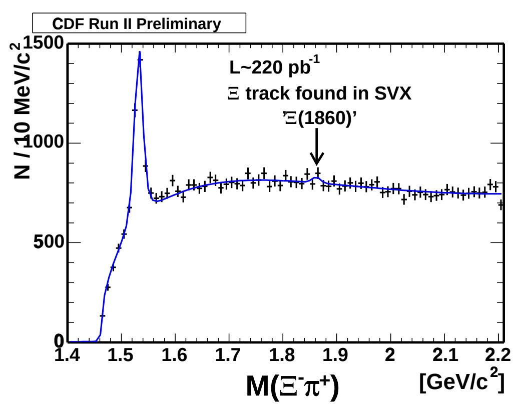

Figure 4: The invariant mass spectrum for $\Xi^-\pi^+$ whose hyperons have tracks successfully reconstructed in the SVX II. The track pairs form the vertex fitted with two-dimensional $\chi^2_{r\phi} < 36.0$. The two displaced track trigger data sample of integrated luminosity $\mathcal{L}$=220 pb^{-1} is used. The fit to a Breit-Wigner convoluted with a Gaussian finds 2182±92 events in the peak for $\Xi^*(1530)^0 \rightarrow \Xi^-\pi^+$. The peak is used as a gauge signal for pentaquark searches. The similar spectrum (not shown here) in the inclusive jet E_T >20 GeV sample yields 387±34 events for $\Xi^*(1530)^0$. The pentaquark signal region at 1862 MeV/c^2 is fitted with a Gaussian of a fixed width σ =8 MeV/c^2 predicted by Monte-Carlo simulation.

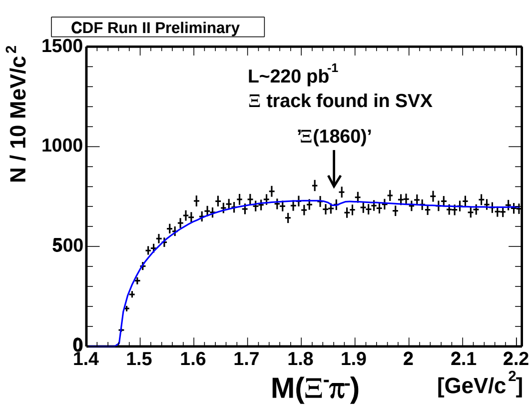

Figure 5: The invariant mass spectrum for $\Xi^-\pi^-$ whose hyperons have tracks successfully reconstructed in the SVX II. The two displaced track trigger data sample of $\mathcal{L}$=220 pb^{-1} is used. The spectrum is fitted by a polynomial background shaped by a square-root threshold function. The NA49 signal region at $M(\Xi^-\pi^-) = 1862$ MeV/c^2 is fitted with a Gaussian of fixed width σ =8 MeV/c^2. A similar spectrum (not shown here) is observed for the inclusive jet E_T >20 GeV sample.

The spectra $M(\Xi^-\pi^+)$ (Fig. 4) and $M(\Xi^-\pi^-)$ (Fig. 5) corresponding to neutral and doubly charged cascade pentaquark modes do not reveal any enhancement around M=1862 MeV/c^2 [3]. Similar results have been obtained with the inclusive jet E_T >20 GeV sample. We have set upper limits on the production of pentaquarks decaying via both modes. These are shown in a Table 1 below.

Mode	@90%$C.L.$	@95%$C.L.$
Two Displaced Track Trigger Sample		
$\sigma{\cdot}\mathrm{Br}(\Xi^-\pi^+)/\sigma{\cdot}\mathrm{Br}(\Xi^*(1530)^0)$	0.06	0.07
$\sigma{\cdot}\mathrm{Br}(\Xi^-\pi^-)/\sigma{\cdot}\mathrm{Br}(\Xi^*(1530)^0)$	0.03	0.04
combined statistics	0.07	0.08
Inclusive Jet E_T >20 GeV Sample		
$\sigma{\cdot}\mathrm{Br}(\Xi^-\pi^+)/\sigma{\cdot}\mathrm{Br}(\Xi^*(1530)^0)$	0.06	0.08
$\sigma{\cdot}\mathrm{Br}(\Xi^-\pi^-)/\sigma{\cdot}\mathrm{Br}(\Xi^*(1530)^0)$	0.07	0.09
combined statistics	0.09	0.11

Table 1: Upper limits set for a $\Xi^0_{3/2}$ and $\Xi^{--}_{3/2}$ pentaquark states. The yields were calculated relative to the calibrating signal of $\Xi^*(1530)^0$ seen in both data samples.

4 Summary

The CDF Collaboration conducted a search for doubly strange $S = -2$ pentaquark states in the $\Xi^-\pi^+$ and $\Xi^-\pi^-$ decay modes. The signals of the basic hyperon Ξ^- state comprised ~36000 events in the two displaced trigger dataset and ~4900 events in the inclusive jet E_T >20 GeV dataset. The well established resonance $\Xi^*(1530)^0 \to \Xi^-\pi^+$ was used as a calibrating signal and yielded 2182±92 events from the two displaced trigger sample and 387±34 events from the inclusive jet E_T >20 GeV sample. No evidence of exotic baryon states produced in CDF Detector at Tevatron has been found. Upper limits on production of states in the mass range of ~1862 MeV/c^2 have been set. CDF Collaboration is pursuing a vigorous program of searches for possible pentaquark production at the Tevatron.

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